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Projected thermal diffusivity analysis for thermographic nondestructive inspections

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ABSTRACT

Conventional thermographic processing techniques use raw temperature signal as input data and produce an output signal whose features depend on the technique, with higher SNR improving the detection of existing defects. This paper proposes an innovative method developed from a 3D heat diffusion model by projecting the system to a coordinate plane which provides diffusivity values as improved output data. The results produced by this projected diffusivity method show a direct visualisation of the actual contour of defects producing an improvement in the SNR level higher than 15% with respect to the levels obtained by the conventional processing techniques.

1. Introduction

Infrared thermography (IRT) is a widespread technology used in numerous applications with the main objective of measuring temperature at distance and contact-less [1,2]. The information extracted from the temperature values provides knowledge of parameters involved in different physical processes closely related to heat flow phenomena. This is the case of thermographic inspections of buildings for detecting humidities, electric power lines searching for failures or rotating machines seeking malfunctions or wearing [3–7].

An important application of infrared thermography, which is increasing rapidly, is as Non-destructive testing (NDT) tool for detection of defects inside materials. Many of these applications are related to the control of health state and quality assurance of materials subjected to severe regulations, such as composite materials in aerospace industry [8–10]. However, the broad applicability of IRT makes this technology also used for detection of defects in other types of materials such as ceramics [11,12], concrete [13,14], wood [15,16] or even in artworks [17,18], among others. The evaluation of an intentionally induced heat flow makes the detection of anomalies inside material possible without the need for destroying them. The radiation measured by an infrared sensor is related to temperature changes produced by a heat flow inside the material under inspection. Unexpected changes in temperature values imply emergence of indications which may eventually correspond to actual defects.

Nowadays temperature values measured by IRT sensors in NDT inspections are not directly analysed but they are previously processed with mathematical algorithms in order to reduce the level of noise enhancing the defects response. There exists a wide range of processing methods applied to IRT NDT inspections [19–23]. Each processing algorithm is more suited for specific type of materials, defects or heat flow conditions. They take the measured temperature signal as input data and produce output signals with improved features which ease the detection of defects. The type of output signals depends on the processing procedure. Common results are module or phase of complex data, time derivatives and statistical parameters among others.

This paper proposes an innovative method for processing and conducting the analysis of data from thermographic NDT inspections. This method provides an output data related to thermal diffusivity values, obtained by a mathematical transformation of the initial temperature through the use of a 3D thermal diffusivity model under specific conditions. It offers two important benefits: it produces a higher increase in the SNR compared to conventional processing algorithms, which implies a higher detectability of defects, and it also provides a novel way of representing detected defects. This new representation is unaffected by the lateral thermal diffusion effect which artificially enlarge the size of defects so it shows a direct visualisation of the actual shape of flaws.

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2. Infrared thermographic NDT. State of the art

Infrared thermographic inspections basically consist in the measurement and interpretation of the temperature field in the external surface of an object under observation. Variations in thermal properties inside a material produce differences in the distribution of a previously established heat flow, and consequently indications in the observed area emerge making these anomalies visible for an IR sensor.

Infrared thermography (IRT) for non-destructive testing (NDT) is a proven technology that offers reliable information about surface and subsurface anomalies. IRT for NDT is an active methodology, i.e. an external stimulus is applied to the surface of the inspected specimen causing a non-stationary heat flow. The evolution of heat flow is observed by an infrared camera that records the radiation emitted by the surface of the target at a specific wavelength range in the infrared spectrum, representing these results as images, called thermograms. The acquired information is transferred to a computer for later interpretation, or post-processing.

The external controlled stimulus is necessary to induce relevant thermal contrasts between defective and non-defective areas in the specimen under examination. Different methodologies exist in the application of IRT NDT depending on the type of stimulation technique employed. However, most of them can be classified as optical, mechanical or inductive. Optical stimulation uses light to deliver energy to the specimen. In the case of mechanical stimulation, energy is applied to the specimen by means of mechanical oscillations using, for example, an ultrasonic transducer; and inductive stimulation uses magnetic fields to induce currents in the material.

Selection of appropriate stimulation technique adapted to the type of material to be inspected is a key point to guarantee a correct detection of possible defects. However, sometimes even with the application of the suitable stimulation technique some subsurface anomalies are so subtle that the signal levels associated to them are lost in the thermographic data noise. In these cases, the visual inspection of the acquired thermographic data, temperature values, does not provide positive results. Therefore, one extended action is to apply post-processing techniques in order to improve the signal-to-noise content of thermographic data. These methods optimise the location and visualisation of defects, greatly increasing the defect detection rate of IRT. Typical processing techniques are, among others, polynomial fitting and derivatives, spectral analysis and statistical moments.

Polynomial fitting and derivatives. Polynomial fitting is a common enhancing and filtering method in thermographic inspections. This method fits the temperature time history of each pixel to an n-degree polynomial as shown in Equation (1). Then, the resulting polynomials are differentiated to produce successive derivatives [21]. The differentiation of these polynomials produces an increase in the SNR reducing noise content since they are calculated from the fitted data.

$$T(t) = a_n t^n + a_{n-1} t^{n-1} + \ldots + a_1 t + a_0 \tag{1}$$

Polynomial fitting process is in principle applicable to any signal shape.

Spectral analysis. In order to conduct a spectral analysis the temperature time history of each pixel is transformed into the frequency domain using the Discrete Fourier Transform. This method applied to OPT is called Pulsed Phase Thermography (PPT) and combines the advantages of lock-in modulated and pulsed IRT [24]. Spectral analysis is performed with the Discrete Fourier Transform (DFT) on the temperature time history of each pixel using Equation (2), where i is the imaginary number, n is the frequency increment, and Re_n and Im_n are the real and imaginary parts of the DFT. The phase is normally the parameter which provides the most valuable information and is finally computed using Equation (3).

$$F_n = \sum_{k=1}^{N-1} T(k) e^{\frac{2\pi ikn}{N}} = Re_n + Im_n \tag{2}$$

$$\phi_n = \arctan\left(\frac{Im_n}{Re_n}\right) \tag{3}$$

Statistical moments. Among statistical moments skewness and kurtosis may be highlighted [20]. Skewness of a random variable is the third standardized moment, and it measures the asymmetry in a set of statistical data. The balanced normal distribution has a skewness of zero, negative skewness means that data points are skewed to the left, and positive skewness means that data points are skewed to the right. Skewness is defined for univariate data $x_1, x_2, \cdots, x_N$, as shown in equation (4), where μ is the mean, σ is the standard deviation, and N is the number of data points.

$$S = \frac{\sum_{i=1}^{N} (x_i - \mu)^3}{(N-1)\sigma^3} \tag{4}$$

Kurtosis of a random variable is the fourth standardized moment. Kurtosis measures whether the data are peaked or flat. Data with high kurtosis have a distinct peak and heavy tails. On the other hand, data with low kurtosis have a flat top. Kurtosis is defined for univariate data $x_1, x_2, \cdots, x_N$, as shown in Equation (5), where μ is the mean, σ is the standard deviation, and N is the number of data points.

$$K = \frac{\sum_{i=1}^{N} (x_i - \mu)^4}{(N-1)\sigma^4} \tag{5}$$

3. Proposed method

3.1. Heterogeneous isotropic 3D diffusion model

The thermal process that takes place in IRT NDT inspections and makes possible the detection of defects inside a material is properly described by the heat diffusion equation. This equation is the starting point in the definition sequence that leads to the proposed method. However, a model which represents the thermal conditions involved in the inspections as well as the physical properties of the material under analysis has to be defined before starting this definition process.

The first stage in the IRT inspection procedure is the thermal stimulation of the material. This stage can be conducted in many ways using various heating strategies as previously mentioned. Here we consider an optically excited thermographic inspection due to experimental capacities, but in reality any other heating source could be considered. As a result of this election this stage is modelled by the illumination of the outer surface of the object.

In real optical thermographic inspections certain amount of the incident energy is absorbed by the object surface, increasing the internal energy and consequently its temperature, another amount is transmitted in transparent materials, and the rest is reflected to the environment so that the law of conservation of energy is verified. Additionally, inherent heat transfer by convection and radiation takes place between the material surface and the environment although this quantity of energy is negligible. Under usual test conditions the heating process generates temperature gradients at the surface of the specimen under inspection, creating thermal waves which are transmitted into the material by heat conduction. Surface or subsurface anomalies cause perturbations in the propagation of these thermal waves which produce variations in the local temperature of the surface.

This whole thermal process is performed on a material object which has specific physical properties. The existence of defects inside the object may cause different behaviours depending on the thermal properties of the base material and the defect itself, acting like a thermal barrier, reducing the thermal diffusion, or improving the diffusion on the contrary. For the definition of the analysis model a generic